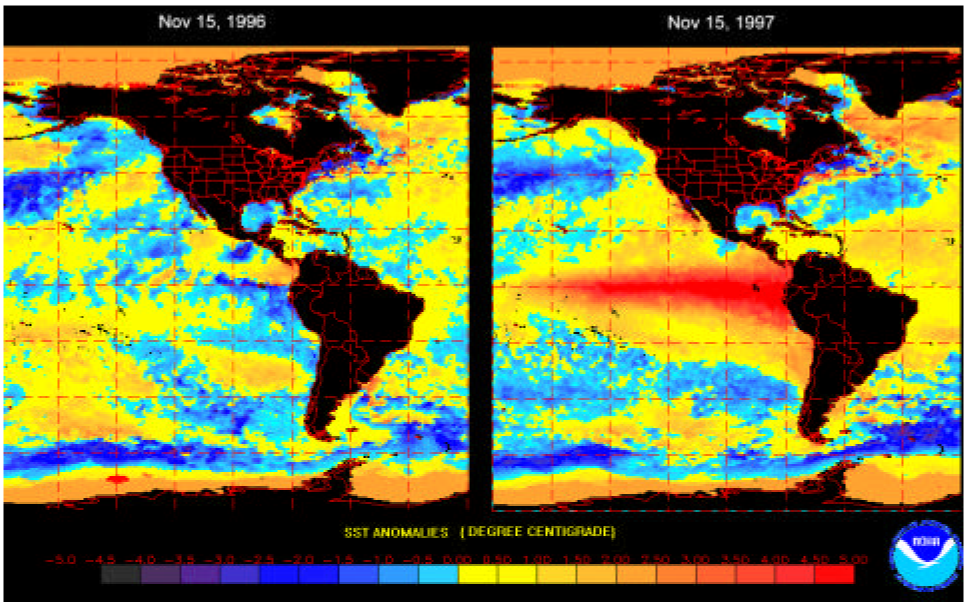
Final Report of the NOAA Science Advisory Board's Panel on Strategies for Climate Monitoring



AVHRR Sea Surface Temperature Anomalies (Degrees Celsius)
November 1996 versus November 1997

Dr. Alfred M. Beeton, Chair
NOAA Science Advisory Board

Dr. Richard M. Goody, Chair
Panel on Strategies for Climate Monitoring

March 26, 2001

Washington, DC

PREFACE

The National Oceanic and Atmospheric Administration's (NOAA) mission is to predict and assess changes in the Earth's environment, and conserve and wisely manage the Nation's coastal and marine resources. The NOAA Science Advisory Board (SAB) recognizes the importance of NOAA's role in climate monitoring, and the central role it plays in climate-related activities. Therefore, the NOAA SAB, at the request of Dr. D. James Baker, recent past NOAA Administrator, noting the specific need for a scientific strategy for climate monitoring, established an ad hoc working group Panel on Strategies for Climate Monitoring in October 2000 in order to address this issue. After review of this report by the NOAA SAB, it will be forwarded on to the new NOAA Administrator for considerations of the recommendations contained herein.

The panel's strategy included a recognition of the need to separate climate monitoring objectives into operational and research components. Both components involve long-term commitment. The panel also provided an overall strategy, based upon existing documents and the panel's own work, and made programmatic recommendations about observing strategies, research management, relationships to other agencies, and any other relevant matters.

As chair of the NOAA SAB, I would like to extend my sincere thanks to Dr. Richard Goody for his motivation and initiative in seeing the need for such an effort and for agreeing to chair this important Panel. In addition, I wish to thank all of the members of the Panel for taking the time out of their extremely busy schedules in order to complete this report in such a relatively short period of time.

This report was presented at a meeting of the NOAA SAB on March 20, 2001, and was accepted. The SAB would like to extend its thanks to Dr. Goody and the members of the Panel for doing such a thorough job in the relatively short amount of time they were given. In accordance with the charge to the Panel, now that the report has been completed and presented to the SAB, the Panel is officially disbanded.

Alfred M. Beeton
Chair, NOAA Science Advisory Board
Washington, DC
March 26, 2001

I am indebted to the Panel members for their efforts to reach consensus on a policy for Climate Monitoring at NOAA. Our report, understandably, reflects the scientific interests of individuals, but the policy framework is of greater significance and is, I believe, a reasoned response to clearly-stated objectives in the Charge to the Panel.

The Panel was asked to meet first between November 2000 and January 2001, and to present its report to the NOAA Science Advisory Board at its March 2001 meeting. This was very little time in which to reach conclusions on issues of importance both to NOAA and to the US climate program, but the Panel was able to achieve consensus by restricting itself to major issues, with minimum reference to other matters such as programmatic questions.

We were able to meet on two occasions (Appendix A2). On the second of these, the Panel agreed unanimously to the wording of both the Summary and the Conclusions and Recommendations. The body of the report was written by a drafting committee consisting of myself, Jim Anderson, and Roberta Miller. The draft report was sent to members, and their amendments were incorporated, where appropriate, by correspondence.

In the course of this correspondence, Dr. Kevin Trenberth expressed some reservations with sections of the Panel report, particularly those concerning the Climate Prediction objective of the Charge, and the Panel's response to it. The Charge and its objectives were discussed and agreed to by the Panel at its first meeting which Dr. Trenberth attended. I regret that Dr. Trenberth could not have been present at the second meeting to hear presentations about and discussions of the Climate Prediction objective, or to discuss his differing views with the Panel. Dr. Trenberth has subsequently indicated that he supports the Recommendations in Section 5 of the report.

Richard M. Goody
Chair, Panel on Strategies for Climate Monitoring
Falmouth, MA
March 6, 2001

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A Scientific Strategy for Climate Monitoring at NOAA

Executive Summary

The National Oceanic and Atmospheric Administration (NOAA), with its climate-related facilities and scientific expertise, is the logical agency to undertake the primary responsibility for a U.S. climate monitoring strategy. However, for NOAA to fulfill its role in the U.S. climate program there must be a programmatic new start in climate monitoring. A climate monitoring program alone loses much of its effectiveness if not related to the projection of future climate. The focus should be on gathering information to test and improve our capabilities for projecting and predicting the climate[1]. A program with this priority should:

- Modernize and extend existing surface and *in situ* Climate Data Records (CDR) and Observations;
- Develop an extended program of reproducible Benchmarks both *in situ* and from Earth orbit;
- Improve the effectiveness of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), the NPOESS Preparatory Project (NPP), as well as collateral free-fliers, for climate applications.

A productive program of monitoring must be closely related to its end-use. Numerical climate models now have long-term predictive capabilities and an effective monitoring program should be applied to the inputs (*i.e.,* climate forcings), and the outputs (*i.e.*, the projections) of climate models.

- The NOAA monitoring program must be closely related to an operational climate prediction and climate projection program, as defined in section 3.1, that focuses on the integration of climate observations with models.

A program that combines monitoring with evaluation of model performance provides an important theme for U. S. climate activities. It adds to programs that seek to improve model processes; it can provide information of significance for process studies but does not replace them. In addition to these activities it provides data for NOAA to fulfill its responsibility for "describing the climate as it affects life and property."

- The Agency should seek private and public sector input on monitoring and observational data and information needs and should also fund research and training programs on the use of climate data and information. It should provide adequate support for data access and long-term stewardship.

[1] We distinguish between climate projections, which are scenarios of future climate based on a given set of climate forcings, *versus* climate predictions, which are directly tied to the initial state of the atmosphere, oceans, and terrestrial environment.

In order to carry out this program:

- NOAA climate activities, including monitoring and relationships to both operational and research-related programs, must be combined under a single management structure having the following responsibilities:
    - — Program oversight for all climate-related activities;
    - — The health of climate observing systems as well as all CDRs, including conformity with the ten principles of Climate Monitoring (NRC, 1999);
    - — Evaluation of monitoring programs in the light of the climate prediction and "life and property" objectives through, for example, the establishment of a committee of experts;
    - — To adapt and evolve as new technologies and issues arise;
    - — Open selection of science teams to assist with calibration, validation, and data analyses;
    - — Development of strong collaborations with other national and international agencies.

Climate science is in an early phase of its development, and the quality of its participants is crucial. The long-term success of the climate monitoring program depends on its capacity to attract young, emerging intellects.

1 Introduction

The NOAA Science Advisory Board Panel on Strategies for Climate Monitoring was charged to consider, "the specific need (*of NOAA*) for a scientific strategy for climate monitoring, the requirements for which were defined in terms of two specific objectives:

Climate Prediction—to "test and improve predictive capabilities of climate models"; and

Protection of Life and Property—to "describe the climate as it affects life and property."

These two objectives are not independent. Improvement of predictive capability for climate is closely related to NOAA's responsibility for predicting future weather and establishing the probability of success in these predictions. The end use of credible climate predictions lies in the protection of life and property, an equally long-standing responsibility of the Department of Commerce (DoC) and NOAA. Taken together, these two objectives can provide a valuable management tool at NOAA to establish priorities for new starts and to evaluate existing programs.

The need for continuing, long-term data on climate is centrally related to prudent stewardship of the Nation's resources and the protection of life and property. Good management suggests that without the capacity to monitor, measure, and predict changes in the climate system, policy makers in both the public and the private sectors as well as individual citizens will be forced to make long-term commitments and decisions related to critical life and property issues in the absence of critical information. The national economy is now better understood because decision makers have access to long-term data on economic trends and changes. Access to knowledge concerning long-term projections regarding the course of climate change will improve decision making regarding the economy and the economic condition by American corporations, state and local governments, and individual citizens.

NOAA is a logical agency to be responsible for a program for climate monitoring because of its mission to provide national capabilities and the supporting infrastructure for research, observing systems, and environmental data and information services. In addition, NOAA has unparalleled experience with managing operational monitoring programs for weather, coastal areas, and oceans. It also maintains operational satellite observing programs, atmospheric chemical baseline observatories, and, finally, it operates data centers for science and policy. These functions, like the functions of a climate monitoring program, fit logically into the role of the DoC. The DoC has a mission to promote American competitiveness "with cutting-edge science and technology and an unrivaled information base" and to provide effective management and stewardship of the nation's resources and assets. Because of this mission, it provides data and information on the U.S. population and economy through the Bureau of the Census and the Bureau of Economic Analysis (BEA); on trade through the International Trade Administration (ITA); and on weather, telecommunications, patents and trademarks, and advanced technology and technical information through NOAA, the National Telecommunications and Information Administration (NTIA), the Patent and Trademark Office (PTO), the National Institute of Standards and Technology (NIST), and the National Technical Information Service (NTIS). Providing long-term climate information is a logical and necessary function of the DoC.

The practical goal of climate monitoring is to have consistent data for long periods of time. Two strategies, taken together, can best achieve this goal: a strategy based on CDRs emphasizing the *continuity* of observations while minimizing *time-dependent* observing and processing *biases*, and a Benchmark strategy emphasizing the *reproducibility* of data. Both are valid strategies, and best use must be made of each.

In order to evaluate a monitoring program, it is essential for the data to be in constructive use. Data for testing climate models cannot be evaluated unless they are continuously used to test and improve climate model predictions. Moreover, the utility of the data for protecting life and property cannot be evaluated unless there are active research programs that examine the effects of climate variability and change on issues of life and property.

This report will outline an integrated program that starts from the Climate Prediction objective of the Charge, proceeds through the climate data required (Climate Monitoring), to the use of the data for testing climate predictions (Modeling), and to the issue of the protection of life and property. This coherent approach requires unified and responsible management.

Although discussed by individual scientists, a monitoring program to "test and improve the predictive capabilities of climate models" has not been a feature of U.S. or foreign climate programs. More typical are "research" programs aimed at improving model capabilities through the study of individual climate process. These two approaches are complementary and supplementary. Model improvement by itself does not necessarily lead to better predictive capability. That can only be demonstrated by comparing model output with observations, provided by a capable monitoring program. Moreover, model improvement may be better defined in the context of reducing the uncertainty of model projections. Projections of the course of climate change may not be tested for decades to centuries; however, we can quantify the uncertainties of ensembles of model projections and act to reduce these uncertainties.

2 Climate Monitoring Systems

Evaluating the predictive capabilities of climate models is not the same as for weather prediction, namely to predict and compare to the weather when it occurs in one or two days' time. Instead, for decadal or centennial predictions, we must examine details of an evolving prediction, and compare appropriate aspects of model calculations with the observed behavior of the Earth system.

However, we first need suitable observations of both input and output data for models, which must be more accurate than weather data, because we are concerned with changes that are significant not from one day to another but over decades or centuries. For example, significant temperature changes from the climate standpoint are on the order of 0.1 degrees Kelvin (K). Consistency at this level must be maintained over very long periods, preferably indefinitely.

2.1 Climate Monitoring from the Surface and *In Situ*

Historical climate data have relied mainly on surface-based measurements, which include remote sensing instruments such as radars and lidars, and *in situ* measurements, which imply making measurements of the immediate surroundings, for example measurements using thermometers at the land surface, ocean buoy measurements, and atmospheric radiosonde measurements.

2.1.1 Climate Data Records

Surface and *in situ* observations, often associated with weather networks, have provided the most important data so far for the detection and attribution of causes of global change. Long-term consistency is usually provided by quantifying and minimizing space- and time-dependent biases and having continuity of records provided by CDRs. Surface data are also used in a variety of applications to reduce climate-related risk to life and property, and often act as anchor points for validating space-based measurements.

For these reasons, the NOAA surface and *in situ* networks constitute an irreplaceable resource that is operating under serious difficulties at a time when there are increasing calls for a capable global observing network, in which NOAA will certainly be called upon to play a leading role.

A major effort is required to produce satisfactory CDRs from operational data. Over the past decade a number of basic principles have been developed for the delivery of long-term data with minimal space- and time-dependent biases. These principles have been endorsed by the National Research Council (NRC) in 1999, the United Nations Framework Convention on Climate Change, and in the recommendations for a Global Climate Observing System. NOAA has been involved in the development of these principles which, if followed, would provide assurance that the NOAA observing systems would be able to deliver long-term, high-quality data for climate and global change analyses.

2.1.2 Shortcomings of the Present NOAA System

The current climate monitoring system relies upon a mix of observations made for other purposes, notably weather forecasting and aviation.

Atmosphere/Land surface. The extreme heterogeneity of the land surface means that high-resolution information is required and must be sustained in the face of the changing landscape, managed systems and urbanization. NOAA does not now provide a number of elements critical to understanding climate, including: land surface boundary conditions including the hydrological components; and atmospheric moisture profiles including information about clouds. The climate is highly sensitive to land surface conditions including soil moisture, snow cover, and vegetation. *In situ* observations of cloud amount, height, thickness, precipitation, and humidity are only grossly measured today. In fact, in many ways, NOAA has less information about cloud amount and heights than it did ten years ago, despite the fact that changes in cloud distributions and amounts have been consistently identified as one of the primary uncertainties in understanding climate change.

Oceans. The oceans are critical for long-term climate projections. But the oceans are observed with nowhere near sufficient detail. Some effective subsystems have recently been developed to monitor the oceans, the most notable being the Tropical Atmosphere Ocean (TAO) array of moored buoys in the tropical Pacific Ocean. There is a need to move systematically toward providing continuous, three-dimensional fields of variables for the ocean: heat content, salinity and currents. Knowledge of the distribution and changes in the heat storage in the upper ocean is a key element in understanding why observed climate variations at the surface have occurred. We need to determine whether the thermohaline circulation is slowing, as some models predict, whether El Niño is looming, and to map other regional changes of vital interest to the health of the ocean. We can foresee expanded needs for tracking of nutrients, ocean blooms, phytoplankton, pollution, pCO_2 and other trace constituents. Initially a goal should be to adequately determine fields on a monthly basis. Major parts of the ocean vary only slowly, and the main need for monthly observations is in the upper ocean. Finally, sea ice is of importance to climate change. It can be monitored from space but thickness, mass and volume are *in situ* tasks, and data are not routinely available.

Forcings. NOAA's network for measuring the elements of climate forcing (greenhouse gases, aerosols, radiation) is currently adequate to characterize global, long-lived, greenhouse gas levels, but inadequate to determine sources and sinks at less than global scales. In all cases, the network of *in situ* measurements is inadequate for determining the relative importance of anthropogenic climate forcings; long-lived greenhouse gases are not measured adequately over continents, and tropospheric ozone and aerosol monitoring are grossly inadequate to characterize all the important global sources. At present greenhouse gas sampling mainly involves clean maritime air. But since the biosphere is an important sink of carbon dioxide (CO_2), the global flask-sampling network should be extended to the continents. Different biomes of major continents (particularly North and South America, and Africa) should be represented in the grid of sampling stations. Atmospheric aerosols need to be characterized on an even smaller regional scale than greenhouse gases. At present NOAA's aerosol characterization sites are limited, and a lack of instrumentation requires that some sites be moved after a few years, so that long-term changes are not recorded. Similarly, while NOAA operates a number of world-class solar and terrestrial radiation monitoring sites at key global locations, the number is limited by the availability of equipment and personnel.

2.1.3 Critical Advances in Technology

Atmosphere/Land surface. NOAA's surface observations are manpower intensive, and the requirements for a global monitoring network can only be met with technological advances, the most important of which is automation. This reduces manpower costs, but requires even closer scrutiny of the observations. Looking ahead, NOAA should be considering the next stages of automation in its networks, *e.g.* robotics. Over land, soil moisture, snow depth, snow water equivalent, visibility, height of the lowest cloud bases, and precipitation should be measured by robotics. Technological advances in local measurements of droplet size distributions are needed. Improved radar technology for the measurement of area-wide precipitation and new technology for cloud imagery from the surface are needed for tracking changes in clouds.

Oceans. Existing global subsurface measurements are extremely limited in temporal and spatial coverage. A few locations are monitored regularly, and volunteer observing ship measurements are restricted to commonly-used shipping lanes. Moreover, data quality and consistency remain serious concerns. Technological and computational developments are needed. These include new ways to improve salinity sampling (such as from Conductivity Temperature and Depth sensors deployed from ships underway), steerable or controllable floats (such as underwater gliders), and improved surface fluxes including from ships of opportunity. Improved models and their adjoints are needed for inverse modeling and data assimilation.

Forcings. Collecting samples for analysis of carbon dioxide (CO_2) and methane (CH_4) as now performed, will be a daunting task for an expanded network, particularly for aircraft samplers with 20 samples on each flight. New instruments to measure directly the vertical profiles of greenhouse gases from aircraft must be developed. Instruments to determine isotopic composition of CO_2, without requiring an air sample, are under development. A combination of *in situ* measurements with sufficiently accurate satellite measurements will be required for future global, source-sink work. In order to properly assess these new carbon cycle data, additional information on changing land-use, vegetation, etc., as provided by other agencies' ground-based and satellite surveys, will be useful.

2.1.4 The Scope of an Ideal *In Situ* Network

The questions to be answered concerning anthropogenically induced global change are so important that the strategic planning of a global *in situ* monitoring system is essential. Because of its mandate NOAA will be called upon to play a leading role in the development of this monitoring system. International cooperation works well for ocean observations, but is more difficult for land-based operations. For this reason it is appropriate first to establish a modern atmospheric and hydrological observational network for the continental United States. A portion of this national program should be the involvement of Universities, perhaps similarly to NOAA's Sea Grant program.

Expansion of a national system to be global through international cooperation should be a high priority. It must satisfy research needs first and move to an operational system in the future. This is the procedure used to develop the TAO array. An adequate global system would be made up of a system of ground stations, balloon-, aircraft-, and space-borne instruments, and samplers. Models to ensure that measurements are made in the right places with the right frequency should guide this observing system.

2.2 Benchmarks

The term *Benchmark* carries particular importance in the context of long-term climate monitoring and with respect to testing the veracity of climate model predictions. The central elements in the definition of a climate *Benchmark* are:

- Accuracy that extends over decades, or indefinitely;
- Variable critical to defining long-term climate change that is observed on the global scale;
- A measurement that is tied to irrefutable standards, usually with a broad laboratory base;
- Observation strategy designed to reveal systematic errors through independent cross-checks, open inspection, and continuous interrogation;
- Limited number of carefully selected observables, with highly confined objectives defining (a) climate forcings, (b) climate response.

2.2.1 Benchmark Quality

The concept of a Benchmark is familiar in the laboratory, where measurements can be calibrated against international standards and are designed to be independent of the experimenter or the equipment used. The same principles can also be realized for a carefully selected sub-set of climate measurements.

Just as the stewardship of *in situ* networks in the pursuit of climate data records demands adherence to fundamental principles (NRC, 1999), the development and discipline of Benchmarks for long-term climate monitoring demand their own principles. For example:

— Accuracy tied to irrefutable standards over time scales of decades requires strict selection of a highly limited number of these Benchmark observations.

— Inclusion as a Benchmark implies global representation of an observable of great relevance to climate modification.

— The link between the rate of change of a given climate variable (for example, temperature, sea level, carbon dioxide mixing ratio) and the period of time over which the observation must detect a given increment of change, sets the requirement for measurement accuracy.

- Achievement of the objectives intrinsic to the definition of a Benchmark demands, in all cases known to date, that the fundamental elements in the instrument design be singularly focused on the accuracy target.
- The combination of (a) the inherent importance of a given Benchmark observation to the testing of hypothesized climate change and (b) the need for scientific consensus on reported observations, places great importance on the mechanisms of open inspection, international visibility and continuing development of crosschecks designed to expose systematic errors in a Benchmark observation.

Global Positioning Satellite (GPS) occultations offer a concrete example of a Benchmark. The only measurement is a time lag, which can be made with such high accuracy that, for climate purposes, the measurement is error-free. For atmospheres with the same physical and chemical structure, this time lag will be the same (given reasonable precautions) whether it is measured by a Russian, a European or a U.S. mission, now or in 25 years time. There are problems to be solved with the interpretation of the time lag, but the measurement itself is a Benchmark.

2.2.2 Some Benchmarks

Benchmark measurements can be made from space or *in situ*. They may be measurements of forcings or of climate response variables. Benchmark measurements are not new to NOAA; a number of existing NOAA programs are of Benchmark quality.

Space missions. Four space Benchmarks were presented to the Panel. Two were atmospheric (GPS occultations and resolved thermal radiances), one concerned the oceans (altimetry), and one was a forcing (solar radiation). Of these, a GPS Occultation Sensor receiver/transmitter (GPSOS), an altimeter (ALT), and a Total Solar Irradiance Sensor (TSIS) are already a part of the NPOESS payload.

GPS occultations have attracted international attention in the past few years. The equipment is of low cost, as space instrumentation goes, and is being installed on a number of missions-of-opportunity. The Taiwan/University Corporation for Atmospheric Research (UCAR) Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission involves a six-orbit constellation. These are encouraging developments, but attention must be given to important details.

To avoid aliasing significant components of the diurnal cycle from polar orbiters requires three or more satellites, at equal time intervals. At the present time planning for GPS occultation measurements is, apart from COSMIC, haphazard. However, the success of COSMIC is not yet assured. As an early contribution to the Benchmark program NOAA should take a lead in coordinating these measurements, and should plan to fill gaps with additional missions-of-opportunity or with low-cost, dedicated spacecraft. A well-designed GPS constellation, together with a program of use of the data for model tests (see §3.2) would be a major contribution to climate science.

The Benchmark quality of space solar radiance measurements can be maintained with occasional calibrations against cryogenic equipment carried on other platforms, *e.g.*, Space Shuttle, and sea-level altimetry measurements, must be normalized against available surface tide stations.

Panel members noted that additional space Benchmarks are feasible. A range of solar occultation measurements, or satellite-to-satellite occultations with radio signals, are self-calibrating. The Stratospheric Aerosol and Gas Experiment (SAGE) measurements, using solar occultations are an example. Measurement of ozone and other atmospheric absorbers using solar occultations can be of Benchmark quality provided that filters or dispersive devices have the required stability, and can distinguish aerosol extinction.

Low-mass, small volume, and low cost are a characteristic of many Benchmark measurements from satellites. When a measurement is narrowly focused on climate applications, many expensive attributes of space missions can be dispensed with. A very accurate thermal Fourier Transform Spectrometer (FTS) [0.1 degrees K accuracy convincingly demonstrable for the entire mission] has been proposed in the $20M range (including launch). At this cost level satellite constellations designed to eliminate diurnal aliasing errors can be considered, particularly with international collaboration.

In situ measurements. Some CDRs have inherent Benchmark quality. NOAA is a major contributor to greenhouse gas monitoring of CO_2, methane (CH_4), nitrous oxide (N_2O), as well as chlorofluorocarbons (CFC) from surface stations. Provided that proper precautions are taken with the exposure and the collection techniques, the measurements come down to laboratory gas standard preparations, which are accurate beyond the needs of climate models.

The Dobson total ozone spectrometer (also a NOAA monitoring instrument) is an interesting example of a surface Benchmark. Reproducibility is assured by standard spectral ratiometric principles. The Dobson instrument was originally constructed in the 1930s. Measurements over almost 70 years are consistent and comparable.

2.2.3 A Benchmark Program

The Panel recommends that NOAA adopt an enhanced Benchmark effort as an important element in its Climate Monitoring program. A management structure is required that can bring together existing programs with new initiatives to create a program unique to the Agency. Important opportunities that arise from low-cost missions and small-satellite technology must be considered. Some possible enhancements to NOAA's present programs are described below. A Benchmark team of scientists and engineers from inside and outside NOAA should be created to examine and to report on these possibilities.

GPS occultation missions must be coordinated, and extended if necessary. The Benchmark team should evaluate the efficacy of the existing *ad hoc* missions and determine the need for new missions-of-opportunity, or dedicated free-flyers. Studies of the assimilation of GPS data are in progress in several scientific groups. NOAA must participate in these studies in order to be able to use the data in conjunction with an operational climate prediction program (§3).

Absolute, spectrally resolved radiance emitted to space is a well-studied concept that yields a rich variety of data on both forcings and responses, and constitutes a key Benchmark that is capable of early deployment. The fundamental observation requires demonstrable accuracy (absolute) of 0.1 degrees K for the duration of a typical mission. In a focused mission, this can be carried out with small satellites of approximately 100 kg all-up mass in low-earth orbit, each containing two bore-sighted Michelson interferometers scanning the spectral interval from 250 to 2000 cm^{-1} with a spectral resolution of ~ 0.5 cm^{-1}. Each interferometer is referenced to two independent black bodies and deep space. With disciplined focus on accuracy, the spacecraft requirements for such a mission are modest: passive thermal control, gravity gradient stabilization, no cross-track or along track scanning, fixed solar arrays and a mean on-orbit power of ~50 watts.

A resolved thermal radiance program should be evaluated by the Benchmark team involving a constellation of missions of opportunity, independent, low-cost missions, and/or combinations of free-fliers with NPOESS and mid-morning orbital plane (METOP) satellites. Data from earlier missions, IRIS (1970) and IMG (1996), may be (and are being) used as surrogates to define the issues that can arise with high-accuracy missions.

SAGE-type Benchmarks should be investigated. Research is required into the appropriate method of obtaining spectral resolution that leads to reproducible absorption measurements. Satellite-to satellite radio occultations do not involve spectral resolution problems, but feasibility requires more study than has been performed to date. SAGE-type occultations may be suitable for very low-cost piggyback missions.

An aerosol Benchmark related to climate forcing is required. SAGE-type occultation measurements are valuable for characterizing the climate effect of stratospheric aerosols related to volcanic eruptions but are not useful for determining the climate forcing of tropospheric aerosols where both the aerosol amount and the scattering *versus* absorption characteristics of the aerosol are important. These aerosol characteristics could be obtained via a scanning multi-spectra polarimeter of high precision. A key characteristic of both such a polarimeter and SAGE is the capability for "self-calibration" that is inherent in their design.

Contributions to small-satellite constellations should be sought from other Agencies, national and international. This is an ideal way to involve small nations, not previously participants in space research (Taiwan is an example).

2.3 NPOESS Climate Data

NPOESS will be the principal NOAA weather satellite observing system for the coming decades. In combination with its international partners, particularly EUMETSAT, with its capable METOP satellites, NOAA will have access to an extremely capable system of sun-synchronous weather satellites.

With the cessation of the plan for repeated launches of Earth Observing Satellite (EOS) satellites (Terra, Aqua and Aura), this international constellation of weather satellites has been seen by the climate community as the best means to obtain long-term climate data from space. We have concluded that NPOESS can, indeed, make a major contribution to climate monitoring but, because there are some real differences between climate and weather requirements, it cannot, by itself support NOAA's requirements for climate monitoring. We also conclude that some specific actions are required to realize NPOESS climate capabilities.

In recognition of the climate capabilities of NPOESS, the NPOESS Integrated Program Office (IPO) commissioned a study in 1996 (UCAR 1997). This study laid out detailed specifications for individual Environmental Data Records (EDR) for incorporation into NPOESS Integrated Operational Requirements Document (IORD) that would lead to better climate performance. A workshop on atmospheric aerosols, held at the Geophysical Fluid Dynamics Laboratory (GFDL) in September 2000, recommended additional EDR specifications to be incorporated into the IORD for aerosol properties, and further recommended that an aerosol instrument be included on the NPOESS Preparatory Project (NPP) mission. The Committee on Earth Studies (CES) of the NRC Space Studies Board (NRC 2000a, b) reviewed the NPOESS program, and identified many questions that had to be solved to obtain satisfactory CDRs, and it found organizational and technical difficulties to achieving solutions.

The focus of the IPO is on weather forecasting requirements, which the Panel agrees to be the correct priority. Nevertheless, we believe that some upgrading towards climate requirements should be possible without endangering this priority, and that such upgrading could also benefit the weather capability. Many of these upgrades can be made within the schedule and fiscal constraints of the NPOESS program.

Climate monitoring requirements are less well-defined than weather requirements and experience has repeatedly shown that optimization of climate capability within budgetary limitations can only be achieved with a close working relationship between project and industrial engineers and teams selected from the most capable members of the science community (U.S. Government, U.S. non-government, and international), and that the best way to achieve this result is through open competition via an Announcement of Opportunity (AO). The Panel does not believe that single contractors or single research groups can fully address these issues, and strongly recommends that the IPO adopt the well-proven AO approach as soon as possible.

The IPO should immediately consider the factors that lead to effective CDRs, including, but not limited to development of pre-launch sensor characterization and calibration studies, algorithms suitable for climate research, CDR validation, satellite overlap strategies, climate data services, including archive and access to NPOESS data. System flexibility should be retained where possible (e.g., spacecraft resources, free-fliers, etc.) whereby new technology can be incorporated into NPOESS.

Because of the complexity of the instruments in question (for example, the ozone instrument will make use ultraviolet (UV) limb scanning—a different method from previous NOAA instruments), it is important that preliminary missions be flown before the launch of the full, converged NPOESS whenever possible. An “early ride” for each of these sophisticated instruments would allow testing and development of inversion techniques in a framework less structured by operational demands, and likely to yield greater benefits for climate science. Moreover, the NPP and the proposed NPOESS-Lite (a mid-morning mission that would fill in the gap between the US and EUMETSAT contributions to NPOESS) are essential elements of a continuity strategy between NASA's EOS missions and NPOESS.

IPO and Benchmark science teams should jointly consider possible combinations of requirements in a way that would enhance both projects. For some instruments, particularly radiometers, it is not possible to combine climate and weather requirements. NPOESS orbits have a sampling bias, and the weather requirements on Cross-track Infrared Sounder (CrIS) make climate accuracy difficult to achieve. But a small Benchmark radiometer could be flown on NPOESS, to improve the temperature accuracy of CrIS, and sampling problems could be reduced by using simultaneous free-fliers in polar orbits or in rapidly-processing, low inclination orbits. Optimization requires constructive interaction between project engineers and science teams.

Finally, it appears that the NPOESS Program may repeat the mistakes of many other major observing systems by not explicitly allowing for an archive and access systems to be integrated into the real-time data processing system (NRC, 2000c). NPOESS long-term climate monitoring is in serious jeopardy without consideration for the long-term stewardship and access to retrospective NPOESS measurements. The scientific community knows that an absence of this kind of commitment leads to an archive where the data go in, but do not easily get out. There is a long legacy associated with the GOES and Weather Surveillance Radar-Doppler (WSR-88D) data that is just now beginning to be partially resolved, after years of frustration. Climate data services should begin now, using NPP data as a guide.

3 Modeling

3.1 Operational Climate Projection and Prediction

The monitoring program outlined above loses much of its effectiveness if not related to its appropriate end-use, which involves the use of data for climate projections and predictions. Without this step there is neither feedback to the monitoring program or expert information on the data for the prediction program. The Panel recommends that NOAA sponsor an operational monitoring program and that the modeling and monitoring programs be combined in the same management structure.

The term "operational" signifies a numerical climate program whose objective is meaningful climate predictions and projections, in contrast to heuristic experimentation.

In the Intergovernmental Panel on Climate Change (IPCC) assessments, the U. S. has been eclipsed by European efforts that have provided various ensembles of projected future climates. There is an awareness in the climate community that this must change. There is a relationship between this situation and the requirement that the Panel sees for a NOAA program. The Agency should either initiate an operational prediction program or collaborate with other agencies to bring one about. The location is unimportant, but there must be a very close relationship with the NOAA monitoring program.

3.2 Data Assimilation and Reanalysis

The use of CDRs and Benchmark measurements to improve the predictive capabilities of climate models is an aspect of data assimilation and reanalysis.

Data assimilation and reanalysis is now a familiar process for numerical weather prediction models. 4D-variable modeling assimilates data (including derived data such as radiances or molecular refractivities) and improves the initial conditions for a weather forecast, and hence the forecast itself. Practical difficulties with inverse modeling presently lie in the way of doing the same for the physical parameters in a climate model. Reanalysis efforts by NOAA's National Centers for Environmental Prediction (NCEP) provide a means to develop a comprehensive set of climate state variables that would not be available through standard data analysis. The time-dependent homogeneity of these fields are not affected by changes in models, but are indeed affected by the continuity and time-dependent biases within the data used for model initialization.

A "cost function" is used to evaluate the difference between predicted and observed climate fingerprints. One fingerprint might be that of a signal resulting from a known climate forcing. The process of model testing is then identical to "detection and attribution," the difference (from a Bayesian point of view) being that the prior probability of model correctness is estimated rather than the prior probability of the forcing. In both cases the natural variability of the climate system creates difficulties.

In a second approach, the natural variability of climate can be used to test models by comparing model and observed time-lag covariances, and basing a cost function on the differences. This tests directly the model's ability to transmit correctly the effect of a forcing through the climate system.

Finally, benchmarks and CDRs can also be used to verify the long-term qualities of reanalyzed data sets which are being developed with the ultimate purpose of improving model performance.

Work in all three areas is currently underway at a number of institutions. An ambitious research program is required to refine these techniques, but it is evident that, given sufficiently accurate CDRs or Benchmarks, methods exist to test and to improve the predictive qualities of a climate model.

4 Other Issues

4.1 Collaborations with Other Agencies

Nine agencies contribute to the U. S. Global Climate Research Program (USGCRP), and each approaches the subject in a way consistent with its mandate and past experience. The program proposed in this report would give NOAA independent responsibility for testing and improving climate models—a major task that is not the responsibility of any other agency. However, the Panel believes that it can only be carried out effectively with close collaboration between NOAA, the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF).

After the results from an operational climate program have been compared with observations it will be necessary to adjust the climate model to correspond with the observed data. Inverse modeling may make it possible to trace the source of error to one or more climate processes, and to give some idea of the corrections required. To go further requires research into the indicated processes or numerical methods, the principal concerns of NSF and NASA.

During the past five years, NASA's interests have focused on single missions exploring climate processes, with emphasis on new technology. For the U. S. to have an effective climate program, NASA programs must be responsive to the information coming out of the NOAA program, and the two agencies must work together very closely, as they have done in the past with weather satellites, and are now doing with the NPOESS-NPP transition. A new element is that cooperation will be required on the scientific as well as the technical level.

Most Benchmark measurements require careful use of established technologies. But new technologies are eventually required and when this happens the NOAA–NASA partnership will depend on NASA's proven skills with technology development.

4.2 Human Resources

Any action taken to bound climate change will engage economic transformations that can only emerge, within our system of legislation, from scientific analysis that is viewed as objective. This places a premium on the depth and breadth of the scientific substance in the NOAA long-term climate program. Lessons in the history of science and public policy have repeatedly demonstrated that observations, instruments, and models required to form the foundation of the scientific system are only as good as the individuals that develop and guide this process.

Treating climate monitoring and the associated projections of climate seriously demands fundamental restructuring of the avenues connecting vital young intellects to the experimental and theoretical challenges central to this problem. Major efforts in micro-electronics, solid-state lasers, materials, data processing, super-computing, detectors, robotics, airborne systems, ocean sampling, *etc.* are required that demand the finest scientists and engineers operating in unison in a competitive domain backed by substantial financial support.

These efforts must be executed in a context of high-quality, long-term standards that are open to criticism and inspection. Many of the required innovations emerge from molecular-level processes that both revolutionize device development and lock the accuracy of key measurements to irrefutable standards. This places stringent requirements on the breadth and depth of preparation in basis physics, chemistry, electrical and optical engineering and on the agility and responsiveness of the scientific and technical environment that seeks to attract this emerging talent.

In order to establish the required path to first-rate, young intellects, it will be necessary to provide graduate and postdoctoral fellowships and open opportunities for scientific and technical development awards to university faculty and small businesses. Full consideration of the developments needed to realize the requirements for the CDRs from the *in situ* networks and the objectives of the Benchmark measurements from space, airborne and ground-based systems underscores the need for innovative programs and structures.

4.3 Management

The program that we propose for NOAA is difficult and challenging, and cannot succeed without capable and responsible management. This will require a substantial change in NOAA top management.

NOAA has many small (and a few large) climate activities that have been organized largely in three different line offices. For example, the National Weather Service (NWS) operates the Climate Services Division, which oversees the Climate Prediction Center and all the weather observing networks. The National Environmental Satellite, Data, and Information Service (NESDIS) operates three Data Centers, the Climate Research and Applications Division, and the NPOESS IPO. NOAA's Oceanic and Atmospheric Research (OAR) line office is a particularly diverse operation. It is responsible for important portions of the climate ocean observing system, for establishing an international climate research institute, and for the Climate Diagnostics Center (CDC). There are six OAR research laboratories with some involvement in climate activities: Aeronomy; Environmental Technology; Atlantic Oceanographic and Meteorological; Geophysical Fluid Dynamics; Climate Monitoring and Diagnostics; and Pacific Marine Environmental. In addition, there are other managerial divisions such as the Climate and Global Change Program.

The program recommended by this Panel involves ground-based observing systems, operational satellites, and Benchmark systems, in addition to an operational climate forecasting facility, international activities, and some responsibility for long-term life and property protection programs. It cannot succeed without a clear and unified administrative and management authority and is incompatible with the existing structure. An attempt to combine the new with the old would court failure, with adverse consequences for NOAA and the national climate program.

A successful management structure must be able to accept strong inputs from the national and international science community. Scientific oversight is essential to examine and interpret results, to trouble-shoot instrument behavior in early design phases, and to work towards improved instruments and management strategies. A scientifically-rooted management structure capable of addressing findings and identifying likely areas for new discovery is required.

These needs argue against a purely top-down management hierarchy. Rather, a successful management structure should actively engage a broad scientific community, retain their interest, and reward their efforts.

A science advisory structure provides one portion of such a system by bringing high-level technical advice to help design and implement climate monitoring plans. The quality climate data to result from such a system will be coin of high value to science, to society, and to policy-makers. Appropriate resources should be put in place to make the data widely available, to provide easy-to use information access points (such as the Internet), and perhaps most important, to assure prompt availability to the scientific assessment process and to policy-makers. A science advisory committee is one of several means to achieve some of these ends, as high-level oversight can help to set appropriate goals and ensure accurate interpretation of the findings.

Advisory groups are, by definition, part time. A more direct involvement is needed if the talents of the broader community are to be brought to bear on the gamut of technical, budgetary, and scientific matters that will make up the challenges of a climate monitoring system. A group of high-quality scientists can only be fully engaged if they are directly involved in the work, forming more than an occasional advisory group. The problem calls for a diverse science team actively involved with research, priority setting in the generation of future products, and instrument design. Such a team should have technical breadth, should be able to make choices among budget and science needs, and should play a major role in future instrument choices. They should be competitively selected from among the broad research community, including U. S. and foreign university participants.

The new management structure that we recommend must have clear responsibility and accountability for NOAA climate activities, and with sufficient, independent budgetary authority. The responsibilities of this new management structure should include, but not be limited to:

- Program oversight of space-based, ground-based and airborne climate activities.
- Development of improved ground-based and *in situ* networks.
- Ensuring that climate data records adhere to specific principles that ensure consistency.
- Critical judgment on the selection of Benchmark observations that accurately track long-term trends in key climate indices
- Decisive strategies for linking observations with modeling efforts, that can lead to maximum credibility for NOAA climate projections.
- Real time access and quality assessment for all climate programs in the light of the requirement for better and more useful climate projections.
- Active engagement of the broader scientific community in the continued innovation of the NOAA climate program
- Actively encourage both the development and the incorporation of new technology into the NOAA climate program.

- Recognition of the importance of international cooperation.

5 Conclusions and Recommendations

NOAA management should undertake a programmatic new start in climate based on the following:

- Fundamental reconstitution and modernization of the national and global *in situ* observation networks to provide CDRs and observations by, for example, robotic development, aerosol source and characterization, and carbon source/sink analysis.
- Acting on the fundamental need for selected Benchmark observations—observations that can be reproduced with defined accuracy at any future time—that accurately specify long-term migration of key climate forcings and responses. Examples include GPS occultations; *in situ* observations of CO_2; solar irradiance; and spectrally resolved, absolute radiance emitted to space.
- Ensuring the capacity of NPP and NPOESS to address climate change issues. This demands selection and funding of broad competitively-selected science teams drawing on experts not only within NESDIS, but also from other parts of NOAA, the university community, NASA and other agencies and internationally. For example, these teams would develop and implement strategies for sensor calibration, algorithm development, and validation.
- A comprehensive re-examination of the structure and objectives of climate modeling that (a) confronts the credibility of long-range climate predictions; (b) links specific observations to the mechanisms intrinsic to the models; (c) provides the structure for assimilation of diverse observations; and (d) implements models to design and improve measurements strategies.
- The provision of adequate access to data and information from both space-based, ground-based, and *in situ* observing systems, and the long-term stewardship of these data must be given equal priority with that of making the measurements. Additionally, the Agency should seek private and public sector input on monitoring and observational data and information needs and should also fund research and training programs on the use of climate data and information.
- A management structure for the NOAA climate activity with clearly defined responsibilities that include: (a) decisive strategies for linking observations with modeling efforts; (b) oversight of space-based. ground-based, and airborne networks to ensure that NOAA's Climate Data Records adhere to the Fundamental Principles of Climate Monitoring; (c) critical judgment on the selection of Benchmark observations that accurately track long-term trends in key climate indices; (d) active engagement of the broader scientific community in the continued innovation of the climate program; (e) encouragement of both the development and the incorporation of new technology into the NOAA climate program; and finally; (f) recognition of the importance of the international component.

Appendices

A 1. The Panel's Charge

A 2. Meeting Schedule and Panel Membership

A 3. Acronyms

Appendix A1 The Panel's Charge

The Panel will review the requirements for long-term monitoring in order to meet NOAA's mission to predict and assess the climate as it affects the human condition and to test and improve the predictive capabilities of climate models. The Panel will define a strategy for obtaining time-dependent measurements of climate parameters (both climate state parameters and climate forcing parameters) including, but not limited to**:** changing greenhouse gases, aerosols, volcanic emissions, and solar radiation using a combination of satellite monitoring, ground-based monitoring, *in-situ* measurements, and global modeling.

The panel will focus upon specific, important parameters for which the required accuracy is attainable. In addition, the panel will consider existing plans for operational satellites and other systems, such as low-cost satellite systems and new technologies that are ready for operational use.

The Panel will consult with NOAA, the National Aeronautics and Space Administration and the Department of Defense to ensure that new technology, science, and on-going and proposed missions are adequately represented in the study.

Appendix A2 Meeting Schedule and Panel Membership

The Panel held two meetings during the periods of November 15-17, 2000, and January 4-5, 2001, in the main Department of Commerce Building in Washington, DC.

The full agendas and minutes for each of the meetings are available from the Panel Secretariat, Howard Diamond, by contacting him at howard.diamond@noaa.gov.

The following Panel members were in attendance at the respective meetings:

November 15-17, 2000:

Richard Goody, Panel Chair
Mark Abbott, Oregon State University
James Anderson, Harvard University
Roberta Balstad Miller, CIESN at Columbia University
James Hansen, NASA
David Hofmann, NOAA//OAR/CMDL
Thomas Karl, NOAA/NESDIS/NCDC
Gerald North, Texas A&M University
Susan Solomon, NOAA/OAR/AL
Soroosh Sorooshian, University of Arizona (NOAA SAB Member)
Graeme Stephens, Colorado State University
Kevin Trenberth, NCAR
Warren Washington, NCAR (NOAA SAB Member)
Howard Diamond, Panel Secretariat (NOAA/NESDIS)

January 4-5, 2001:

Richard Goody, Panel Chair
Mark Abbott, Oregon State University
James Anderson, Harvard University
Roberta Balstad Miller, CIESN at Columbia University
James Hansen, NASA
David Hofmann, NOAA/CMDL
Thomas Karl, NOAA/NESDIS/NCDC
Gerald North, Texas A&M University
Susan Solomon, NOAA/OAR/AL
Soroosh Sorooshian, University of Arizona (NOAA SAB Member)
Graeme Stephens, Colorado State University
Howard Diamond, Panel Secretariat (NOAA/NESDIS)

Appendix A3 Acronyms

ALT	Altimeter
AO	Announcement of Opportunity
AVHRR	Advanced Very High Resolution Radiometer
BEA	Bureau of Economic Analysis
CDC	Climate Diagnostics Center
CDR	Climate Data Record
CES	Committee on Earth Studies
CFC	Chlorofluorocarbon
CH_4	Methane
CIESIN	Center for International Earth Science Information Network
CO_2	Carbon Dioxide
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
CrIS	Cross-track Infrared Sounder
DoC	Department of Commerce
EDR	Environmental Data Record
EOS	Earth Observing Satellite
FTS	Fourier Transform Spectrometer
GPS	Global Positioning Satellite
GPSOS	GPS Occultation
IORD	Integrated Operational Requirements Document
IPCC	Intergovernmental Panel on Climate Change
IPO	NPOESS Integrated Program Office
ITA	International Trade Administration
K	Kelvin
METOP	Mid-morning Orbital Plane Satellite
N_2O	Nitrous Oxide
NASA	National Aeronautics and Space Agency
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service

NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
NTIS	National Technical Information Service
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
PTO	Patent and Trademark Office
SAB	Science Advisory Board
SAGE	Stratospheric Aerosol and Gas Experiment
TAO	Tropical Atmosphere Ocean
TSIS	Total Solar Irradiance Sensor
UCAR	University Corporation for Atmospheric Research
USGCRP	U. S. Global Climate Research Program
UV	Ultraviolet
WSR-88D	Weather Surveillance Radar - Doppler

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